Measurement of the ac power loss of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ composite tapes using the transport technique

S. Fleshler, L. T. Cronis, G. E. Conway, and A. P. Malozemoff
American Superconductor Corporation, Westborough, Massachusetts 01581

T. Pe, J. McDonald, and J. R. Clem
Ames Laboratory, United States Department of Energy and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011

G. Vellego and P. Metra
Pirelli Cavi SpA, Divisione Italia, 20126 Milano, Italy

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The transport self-field ac loss voltages of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) multifilamentary tapes depend strongly on the voltage lead configuration. We have measured the loss voltage as a function of the measuring circuit loop size defined by the voltage leads and the tapes for well-defined lead geometries. The loss signal was found to reach a limiting value when the length of the loop transverse to the tape was several times the tape width. This limiting voltage represents the ''true'' self-field ac loss as predicted by new theoretical analysis.

Ag-sheathed (Bi-2223) tape conductors provide the potential for a host of superconducting applications at elevated cryogenic temperatures. Some of the most attractive applications require these conductors to perform well upon the application of an ac current and/or an ac magnetic field. The ac power loss of the superconducting wire is a major factor in assessing the application's economic viability, and thus, must be well-understood.

The two most commonly used methods to extract the power loss are electrical techniques in which either (1) currents are induced in the superconductor by the application of an ac magnetic field and a voltage proportional to the electric field is generated in a pickup coil surrounding the sample (the magnetic technique), or (2) current is driven in the sample and the resulting longitudinal voltage is measured with electrical leads attached to the sample (the transport technique). In both cases, the power dissipation is related to the part of the voltage which is in-phase with the driving signal [magnetic field in (1) or current in (2)]. However, the current flow pattern generated in the conductor is not the same for the two methods. Moreover, because the Bi-2223 system is anisotropic, and these bulk materials are inhomogeneous, it is not obvious that the power loss for such tapes obtained using these two different methods can be directly related. This is supported by studies that have found the ''apparent'' power loss measured using the transport technique to be one to two orders of magnitude larger than that measured using the magnetic technique.[1–3] Thus, from a practical standpoint it is essential in Bi-2223 tapes to choose the measurement technique to simulate as closely as possible the operating conditions of the application of interest. In particular, for an application in which the predominant currents are driven rather than induced, such as the power transmission line, utilization of the transport technique is required.

Several authors have recently demonstrated that the apparent loss voltage in monocore Bi-2223 tape conductors measured using the transport technique depends on the position of the voltage leads when the driving current is well below the critical current.[4–6] This dependence of the apparent loss voltage on the location of the voltage leads has led to some skepticism as to the validity of the transport technique when applied to these tape conductors. Campbell has recognized that this positional dependence on the leads arises from the asymmetry in the magnetic flux distribution near the sample due to the high aspect ratio of the conductor.[7] As the voltage leads are placed at different positions relative to the center of the sample, the flux captured by the measuring circuit changes, and correspondingly, so does the total voltage signal induced. This voltage signal carries a lossy component since the flux distribution is hysteretic. Ideally, the voltage leads should be brought far from the tape before twisting to encompass all of this loss flux contribution, although it was suggested that smaller loop would be adequate from a practical point of view.[7] This suggestion requires a modification to the common practice of twisting the voltage lead wires at the surface of the tape to minimize the pickup which is assumed to be an unwanted quadrature voltage. In this letter, we show experimentally that by choosing to close the loop circumscribed by the conductor and the voltage leads several tape widths from the conductor, a limiting voltage is obtained from which the true transport loss can be determined directly.

The transport losses were measured on 30 cm sections cut from production scale lengths (~225 m) of Bi-2223 multifilamentary wire manufactured at American Superconductor Corporation using an oxide powder in tube (OPIT) method.[8] Two multifilamentary wires with 61 and 85 filaments were studied with fill factors of 35% and 22%, respectively. A standard four probe measurement, with a 25 cm voltage tap separation, was employed to obtain the dc and ac transport voltages. The value of the dc critical current (I_c) values for the 61 and 85 filament conductors were 29 and 34 A, respectively, as determined using a 1 μV/cm criterion. Several pairs of voltage lead wires were fixed to two thin G-10 plates in well-defined geometries before soldering them to the sample. The resulting measuring circuits circumscribed by

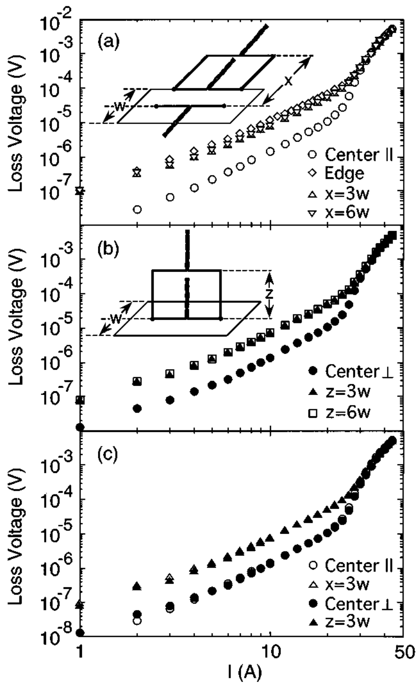

FIG. 1. The rms loss voltage as a function of rms current is shown for the (a) parallel and (b) perpendicular geometries for different values of the length of the measuring circuit transverse to the tape. The wire configurations for the two geometries are shown in the respective insets. A comparison of the ac I–V curves when the leads run along the center of the tape and are closed at a transverse distance of three times the tape width (w) for the two geometries is made in (c).

the tape and voltage wires were rectangles with different transverse distances. The two wires assemblies were mounted parallel to the tape-plane [see the inset of Fig. 1(a)] and normal to the taple along its midplane [see the inset of Fig. 1(b)] which shall be referred to as the parallel and perpendicular geometries, respectively. We denote the transverse distances that the voltage leads are brought away from the tape before twisting them as x for the parallel geometry and z for the perpendicular geometry. For leads placed along the center of the tape, we distinguish between two geometries: one in which the twisted part of leads are brought away parallel to the tape (labeled center ∥), the second way in which they are brought away perpendicular to the tape (labeled center ⊥).

Current was supplied to the samples with a Valhalla current calibrator voltage-controlled by a synthesized function generator. The voltage across the sample was measured with a dual phase lock-in amplifier whose phase was established with the voltage across a noninductive shunt in series with the sample. The phase setting and intrinsic response of the lock-in amplifier were sufficient to obviate the use of a compensation voltage for the quadrature component. The time-averaged power loss was calculated from the product of the rms current and the rms voltage in-phase with the current.

The rms loss voltage as a function of rms current (ac I–V curve) at a frequency of 55 Hz for the parallel geometry is shown for the 61 filament sample in Fig. 1(a). When the voltage leads run along the edge of the tape ($x = w/2$), the loss voltage is larger by an order of magnitude than that when they lie along the center of the tape and are immediately twisted (center ∥), as has been previously observed.[3,5,6] However, when the leads are twisted further away from the tape, the loss voltage actually decreases, reaching a limiting value as demonstrated in the figure for $x = 3w$ and $x = 6w$, where w is the tape width. For the perpendicular geometry, the loss voltage is observed to initially increase by ~10 as the area of the measuring loop is increased [see Fig. 1(b)], and is independent of the transverse distance for loops widths *(z)* greater than $3w$. The agreement of the loss voltages for the center ∥ and center ⊥ geometries provided in Fig. 1(c) confirms the reproducibility of our measurements. The independence of the limiting voltage on the orientation of the measuring loop, demonstrated by the coincidence of the ac I–V curves for $x = 3w$ and $z = 3w$ also shown in Fig. 1)(c), is strong evidence that a measurement of the true loss voltage has been achieved. A detailed theoretical analysis, to be described elsewhere,[9] confirms that for practical purposes a lead loop width of $3w$ is sufficient for a few percent accuracy in determining the true loss.

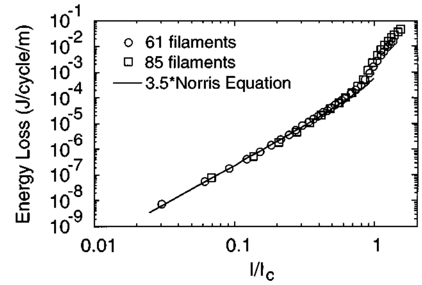

FIG. 2. The dependence of the energy loss per cycle per unit length on the reduced current is displayed for two composite conductors with different filament counts. In addition, a curve proportional to the energy loss predicted by Norris (Ref. 11) for a superconductor with an elliptical cross section is shown.

The energy loss per cycle per unit length as calculated from the true loss voltage is plotted against the rms value of the I_c normalized current for both the 61 and 85 filament samples in Fig. 2. The two samples exhibit identical behavior with an approximate cubic dependence on the current at low values of I/I_c. Our data on multifilamentary tapes is qualitatively similar to earlier results on monofilamentary tapes.[2,10] We also show a curve proportional to the result calculated by Norris[11] for the self-field hysteretic loss (per cycle per unit length) L_e, of a superconductor with a transverse elliptical cross section:

$$L_e = \frac{\mu_0 I_c^2}{\pi}\left((1-F)\ \ln\ (1-F) + \frac{(2-F)F}{2} \right),$$

where $F \equiv I/I_c$ and μ_0 is the permeability of free space. For demonstrative purposes, the average I_c value for the two tapes (31.5 A) was used in this Norris formula. The functional dependence of the energy loss agrees well with the Norris equation deviating from it as the I_c is approached because of the flux flow effects, and ultimately, current transfer to the shunting Ag sheath. However, the value of the energy loss for a given current is ~3.5 times the value predicted by the Norris formula. This discrepancy may arise from an inhomogeneity of the critical current density (J_c) within the filaments. Magneto-optical studies of monofilamentary tapes show that the region near the Ag sheath interface exhibits a larger J_c value than that of the center of the superconducting core.[12] Therefore, the way in which current penetrates the tape during a hysteresis cycle deviates from the standard bulk critical state profile and the Norris formulation. Nonetheless, our results on multifilamentary composite conductors indicate that the dominant mechanism is hysteresis in the superconducting filaments. Further work is necessary to elucidate how the current is distributed within the conductor under ac transport conditions.

In conclusion, we have measured a limiting self-field loss voltage, which is independent of the measuring loop orientation, by extending the voltage leads only a few tape widths away from the conductor before twisting them. Thus, we have demonstrated it is possible to increase the loop width to values sufficient to obtain reliable loss data and to discriminate against the associated large quadrature signal. The resulting energy loss of our multifilamentary conductors was found to be in qualitative agreement with a hysteretic dominated loss mechanism within the superconducting filaments.

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